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CONTROL AND DATA TRANSMISSION SYSTEM FOR A BALLOON-BORNE ION MASS SPECTROMETER

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A control system for a balloon-borne ion mass spectrometer is described in this report. The system provides the ground based experimenter with a control flexibility approaching laboratory environment. A programmable PCM encoder is used for data transmission.

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CONTROL AND DATA TRANSMISSION SYSTEM

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BALLOON-BORNE ION MASS SPECTROMETER

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INTRODUCTION

A balloon-borne instrument package is currently being developed by the Aeronomy Division of the Air Force Geophysics Laboratory.* The primary instrument is a quadrupole mass spectrometer. Its task is to detect ambient ion and neutral clusters at altitudes of 30 to 40 kilometers. Positive and negative ions in the range of 14 to 1000 atomic mass units (amu) are to be investigated. An aspirated Gerdien condenser and a low emission potential probe are included as supporting instruments. A flight from the AFGL Balloon Facility at Holloman AFB, New Mexico is planned for spring, 1981.

A block diagram of the scientific package including the command and the telemetry links directly associated with data gathering and transmission is shown in Figure 1. All the blocks identified in the diagram are supplied by AFGL with the exception of the exciter and digital control circuits for the ion mass spectrometer (IMS) and the PCM encoder. The electronic systems used to generate the excitation signals for the mass filter and to control the data gathering and encoding processes were developed by the Electronics Research Laboratory of Northeastern University.

A balloon flight that can last 10 to 20 hours is planned. During this long a period of time measured data can differ sufficiently from that anticipated in advance to warrant in-flight changes in the experiment. The attractive possibility of a ground based experimenter interacting with a balloon-borne laboratory considerably influenced the development of the control system for the mass filter.

A microprocessor based system with a great variety of prearranged programs for controlling virtually all the electrical parameters of the spectrometer forms the primary control unit. A closed-loop serial command link allows the operator to access this extensive library and to command the control system to execute any chosen program. In addition a new set of instructions to control the spectrometer parameters may be transmitted to the control unit. A preprogrammed combinational logic control unit serves as a back-up. More limited in its capability than the primary system, it provides a few choices of canned programs accessible through the tone command link.

In addition to the real time data transmission, the mass spectrometer data is also stored in a RAM for a delayed transmission. Data is transmitted through a PCM/FM telemetry link. A programmable encoder with nine eight-bit direct access channels and 48 analog inputs formats the data into a PCM stream.

In what follows, a brief description of the mass filter and the necessary conditions for its operation are given. Then the principles and capabilities of the digital control system are described. Finally the details of the PCM encoder developed for the balloon-borne scientific package are presented.

MASS SPECTROMETER

To perform the mass analysis a quadrupole mass filter is employed. This spectrometer shown in Figures 2 and 3 consists of four parallel rods where the opposite rods are electrically connected. The excitation signals consist of a dc component, U, and a radio frequency component, $V \cos \omega t$. A common bias voltage, Q, is connected to both sets of rods. As a consequence of this, a unique oscillating electrical field exists between the rods. An ion

* Work at Northeastern University is supported under Contract No. F19628-78-C-0218.

injected in the longitudinal direction into the quadrupole region oscillates between the electrodes of opposite polarity. At a specified frequency, ions of a given mass undergo stable oscillation between the electrodes as they travel at the injection velocity towards the collector. Ions of lower or higher atomic mass undergo oscillations increasing in amplitude until they strike the quadrupole rods. The range of mass stability is defined by the ratio U/V while the location of that range within the whole mass spectrum is determined by $k\ V/\omega^2$, where k is a constant containing the dimentional parameters of the quadrupole. When the ratio is set to zero, the mass filter assumes the high pass characteristics where all ions above a preset atomic mass strike the collector. When the ratio $U/V_{rms} \simeq 0.236$, then at least theoretically, only one species with an atomic mass determined by the amplitude and the frequency of the RF signal will reach the collector. For ratios higher than this value, no ions are collected. For practical reasons a mass filter is usually operated in the band pass mode with the ratio set as close to the maximum value as feasible to increase resolution without sacrificing sensitivity. Wider mass bandwidth as well as the high pass mode is also often employed in atmospheric measurements. Since a linear relationship exists between the amplitude of the RF voltage and the selected mass, a mass scan is performed by varying the amplitude of the RF signal while keeping the ratio U/V constant. A number of electrodes and bias voltages are employed to focus and to inject ions into the quadrupole filter.

An atmospheric pressure ionization source ionizes neutral species when the instrument operates in that mode. A cryogenic vacuum pump reduces the ambient atmospheric pressure to the levels acceptable to the mass filter. Discrimination between the positive and the negative ion species is accomplished by an appropriate biasing of the focusing system and the rods. To detect ions with atomic mass units reaching 1000 an RF signal of 550kHz and up to 3000V peak is applied between the opposing rods. The dc component of the excitation signal ranges up to 500V and the other bias signals have ± 50V limits. A pulse counting technique is used to detect the ions striking an electron multiplier.

Two control modes are used to exercise the bias and the excitation signal circuits associated with the mass filter. Data flow is also affected by the control modes. The primary system is built around the 8085A microprocessor, while the back-up is a CMOS programmable combinational logic unit. Both systems merge into a single bus like structure leading to the mass spectrometer circuits. The control of the mass filter may be transferred between the two systems in a toggle like fashion through a single channel of the tone command link.

All commands to control the basic functions of the mass spectrometer are processed by the combinational logic unit. Functions such as switching ON or OFF the RF and HV circuits, changing the operating frequency of the PCM encoder, selecting the MPU or the combinational logic unit to control the mass filter, and enabling or disabling the count correction mode are all selected via the tone command link. One channel each is used for each choice in a toggle switch fashion.

DIGITAL CONTROL

Of the two systems the MPU based system provides most flexibility in the control of the mass spectrometer. It has an extensive library of instructions to exercise the electrical parameters of the mass filter. A 16 kbyte RAM provides temporary data storage. Limited on-board data processing is also available. Communication with a ground based operator can be accomplished through a closed loop serial command link.

The parameters defined by each instruction are listed in Table 1. The first two instructions define the range within the mass spectrum over which the instrument is to scan. The next two instructions define the number of times the scan is to be repeated and the time that the instrument will spend in gathering data at each excitation signal increment.

The count adjustment flag initiates a process where after a data gathering interval the ion flow to the electron multiplier is stopped and the counter is switched to the countdown mode to subtract any random noise pulses originating in the mass filter. This procedure is necessary in certain amu regions where the number of ions reaching the multiplier during a given time interval may be close to the number of random noise pulses generated by the instrument. This flag is ignored when an ion count exceeds a predetermined level.

Usually the bias voltages are held constant while the mass filter scans through a spectrum of the amu's. Bias polarity is switched only when ions of different polarity are to be investigated. To establish optimum bias levels for a given set of conditions a mode of operation is available in which the bias voltages may be swept. In this mode the amu scan signal is set to detect a single species of interest while one or more selected bias voltages sweep between two levels. The control over these options is maintained by flags b and c and the instructions 7 through 9.

Table 1

1. Start of an amu scan.
2. End of an amu scan.
3. Number of times to scan.
4. Dwell time at each scan level.
5. Ratio control.
6. Flags:
   a. Count adjust mode.
   b. Bias sweep mode.
   c. Scan mode.
   d. High pass mode.
   e. Cummulative count mode.
   f. Positive or negative ions mode.
7. First set of five bias voltages.
8. Second set of five bias voltages.
9. Bias sweep mask.
10. Instruction identification code.

Yet another mode of operation is controlled by the cummulative count flag. In this mode the mass filter repeatedly scans at a fast rate over a range of amu domains. The count obtained at each of the scan increments is accumulated in the RAM. In this mode a wide portion of the spectrum may be investigated within the same interval of time. And finally each set of instructions is identified by a code.

A set requires 32 bytes of memory. One or more sets are assembled into programs. These in turn are grouped into repertoires and finally the repertoires form the library. The library index consists of starting addresses of the repertoires. The repertoires are again a collection of starting addresses of programs which in turn define the starting addresses of the instruction sets. Thus the same instruction sets and programs may appear in different repertoires.

Left to its own devices the MPU control will proceed sequentially through the whole library and if permitted will repeat the process indefinitely. This prearranged sequence may be interrupted by a ground-based operator. The experimenter may send instructions requesting the MPU unit to run one or more of the prearranged programs, or even single instruction sets. The operator also has the option to send a completely new instruction set to be executed by the control system.

The messages for the balloon-borne MPU unit are first entered into a memory in the ground support equipment. A limited number of keys are available for that purpose. All commands are entered by single key strokes while the text may be entered in a hexadecimal, decimal or binary code. Thirty-eight command and 16 hexadecimal keys are available for that purpose. External equipment with an RS-232C interface also may be used to enter data. In all cases the ground support unit translates the entered code into a code acceptable to the MPU. Each time the balloon based control unit completes the execution of a mass spectrometer instruction set, it transmitts an inquiry to the ground station to determine if there are any pending messages. When no messages are available the ground support equipment responds with an end of text character. When a message is available the ground based unit responds with the start of text character and begins feeding the text to the transmitter. Each eight bit character is repeated three times. An acknowledgement of a correct reception by the MPU is awaited before the transmission of the next character. The MPU accepts a character when a two out of three match occurs. It acknowledges reception by an echo to the ground station. Otherwise a request for repeat is transmitted. The retransmission to the ground may proceed either through the serial downlink transmitter or through the PCM/FM telemetry link. Both the air-borne and the ground based command receivers provide AGC signal to their associated processor units to verify the viability of the communications link.

The MPU also controls the flow of the experimental data. Whenever new data has been collected the control unit updates the mass spectrometer circuits and upon request supplies that data to the PCM encoder in an appropriate sequence. When no new data exists, the previously collected data is repeated. The data is also stored in the 16 kbyte RAM for a delayed transmission. An identification heading consisting of every new set of instructions for execution as well as flight time are written in the RAM. Following this heading the ion counts obtained and associated amu identifications are sequentially stored. At the next update in the program the process is repeated.

The data from the RAM is read out over the PCM/FM telemetry system. The transmission may be initiated by the operator on the ground or by the MPU when it calculates that an overflow will take place upon the execution of the next instruction set in the program. Before transmission the data is normalized into counts per second with the help of an arithmetic integrated circuit. This is accomplished during a warning period to the ground based operator of the impending RAM data transmission.

One of the most obvious advantages of the temporary storage process is the rapid rate at which data can be transfered to a recording device on the ground. This feature eliminates the large amount of practically useless recording tape footage usually acquired during very slow data gathering periods. The real time data transmission may be continuously recorded on temporary basis until it can be established that a good transmission of data from the RAM has been achieved. The ability to delay or to repeat the transmission during periods of poor reception presents another advantage. The major advantage of real time transmission and data processing lies in the fact that the experimenter is able to adjust the instrument to fit the existing conditions, to direct its operation towards the unexpected and to reexamine the unexplained.

The programmable combinational system is somewhat limitted in its capability. It lacks the computational power and the access to the RAM. Thus the delayed transmission mode is not available. It does have a rather extensive library of instructions to control the mass spectrometer. The instructions are also arranged in programs and repertoires. A limitted selection of these is possible through the tone command link using two channels. The command signal is a 12 bit word. The eight most significant bits form the recognition pattern while the 4 LSB's represent the command.

PCM ENCODER

The experimenters' data will be transmitted over PCM/FM link. To that end a software programmable NRZ-L PCM encoder shown in Figure 4 has been developed. The format of the PCM signal is determined by a program residing in an EPROM. This approach offers a greater flexibility in format modifications and in data handling than the options available in the encoder where the format is predetermined by a wired logic. The encoder uses an eight bit word length and can accomodate up to 16 different signals. Two of the channels have been hard wired to produce a 16 bit frame synchronization sequence. Two other channels have been dedicated to the resident A/D converter. Spectrometer data, submultiple frame identifier and a counter to determine the number of ONE's within a minor frame are assigned three more channels. This leaves nine eight bit direct access channels for other uses. One or more of those may be shared in a bus like arrangement. Users of the bus must isolate their systems by tri-state buffers which are controlled by the encoder through one of the six (expandible to 16) lines provided for that purpose. Once selected the user port remains active for the duration of one PCM word. The actual data transfer into the pulse train takes place during the last half of the eighth bit of that period and is indicated by a pulse on the LATCH line common to all users of the bus.

In addition to the direct access digital channels, the encoder also accomodates 48 analog signals. The channel selection is accomplished through a six bit binary code. When anyone of the analog input channels is selected for data processing, SAMPLE, HOLD, and CONVERT signals are automatically generated and transmitted to the appropriate circuits. The A to D converter provides 12 bit resolution. Most of the analog data processed by the encoder require only eight bit resolution. Therefore, the four LSB's are usually ignored. For those instances when the full 12 bit resolution is required, the 4 LSB's are transmitted as the 4 MSB's of the next word in the PCM frame by selecting the digital channel assigned to that task.

A control word consisting of two bytes is used to define each word in the PCM frame. The first byte which always resides in the even numbered address locations of 2758 EPROM is used to select one of the 16 eight bit data ports for insertion into the PCM pulse train. Submultiple frame or minor frame program selections and flags to indicate the end of the minor and/or the major frames are also stored in that byte. The second byte of the control word is used to select the analog data channels and to provide controls for the bus users. The EPROM address locations 000H through 0FFH are set aside for the minor frame program. Thus a minor frame of up to 128 words in length may be constructed. Locations 200H through 3FFH are allocated for the submultiple frame routine. Therefore, a total of 256 submultiple frame words may be accomodated within one major PCM frame. The rest of the memory (100H to 1FFH) is reserved to format the PCM frame to be used in the transmission of the data from the 16 kbyte temporary storage.

Once the MPU determines that the RAM does not have sufficient space to store the data to be gathered during the next ion mass spectrometer scan, it suspends data gathering process, sends out through TLM a ten second warning and requests a change of format in the PCM signal. The request is granted at the end of the minor frame, and if no contradicting signals have been received, data transmission from the RAM starts at the end of the ten second warning period. At the end of the dumping sequence, the process is reversed, and the encoder returns to the real time data transmission mode. The nondestructive dumping of the RAM may be delayed indefinitely by a command from the ground transmitted through the serial command link. Also, by request the dumping process may be repeated before the stored data is overwritten by new information.

In order to have some indication of the quality of the transmission within each frame, an eight bit word carrying the count of ONE's in that frame is transmitted just before the two frame synchronization words. The ONE's in the frame sync pattern and the count word itself are not included in the output. Performing similar counting operation during the data recovery process and comparing the results, the number of non-cancelling errors within the frame may be determined.

Each minor frame begins with an op-code word. This word defines the mode of operation of the mass filter control circuits as well as of the encoder itself. It indicates whether the mass spectrometer operations are under the MPU or the wired logic control. It also indicates if the data from the mass filter transmitted in the present minor frame is a new valid information or not. This validation is necessary since the data gathering process by the mass filter may span several minor frames. Meanwhile old data or random sequences, depending on the control mode, may be transmitted in the frame slots assigned to the mass spectrometer data. All data other than the mass spectrometer data is assumed to be valid at all times. The information about the pending PCM format changes are also carried by the op-code word.

Another word always present within each minor frame is used to identify the submultiple frames. It represents the running count of the minor frames within the major frame. During the RAM dumping process this count is used to identify blocks of transmitted data.

The PCM pulse train is also used to "echo" to the ground station the messages transmitted through the serial command link. One of the words within a minor frame is reserved for that purpose. Control over this word is exercised by the MPU, and it is inserted into the frame as a part of the mass spectrometer data.

Presently the encoder may be operated at 12 or 48 kilobit per second rates. The rate selection cannot be controlled by the resident program. Only a command transmitted through one of the channels in the tone command link changes the clock frequency of the encoder.

The lower bit rate is more than adequate for the real time data transmission. At its fastest rate the mass spectrometer is expected to produce new data every 20 ms. This corresponds to a 30 word minor frame. The lower data flow rate also reduces the level of performance requirements for the less sophisticated data crunching equipment used to display the incoming real time data for scrutiny by the experimenter.

In "dump the RAM" mode, the higher bit rate may be desirable. To transmit the 16 kbytes of data from the temporary storage would take a minimum of 11 seconds at the 12 kb/s rate. Combined with the 10 second warning about the impending change in the data transmission mode the dumping process may take almost as long as the time interval used to gather that data. In that case the ground based operator may switch the encoder to the higher bit rate. If necessary, the bit rate of the encoder may be increased to 96 kb/s by a minor wiring modification. This is the highest bit rate at which the encoder may operate. Its speed in the real time data transmission mode is limited by the analog data conversion components. In the RAM dump mode the programming of the MPU limits its speed.

SUMMARY

A highly flexible control system for a balloon-borne mass spectrometer has been constructed. It should provide the ground based experimenter with a level of control flexibility approaching that of an instrument in a laboratory environment. A programable PCM encoder is available for data transmission. The number of available inputs and the relatively simple programming required to modify the format of the PCM signal should accommodate any changes in the data transmission requirements for this or for future scientific packages. The mass spectrometer excitation signal circuits, the control unit and the PCM encoder have been tested as an operating unit. The communications links have been simulated by direct connections since other parts of the balloon package are still under construction. Current progress should readily allow a spring, 1981 balloon flight from Holloman AFB, New Mexico to be realized.

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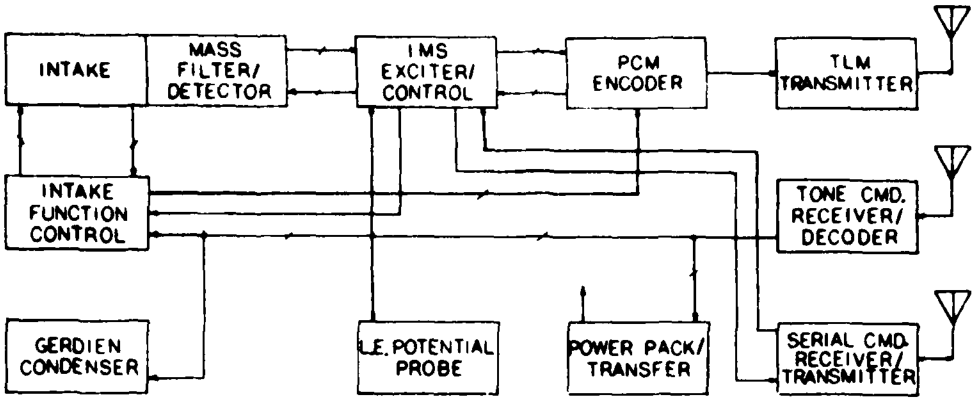

Figure 1. Scientific Package

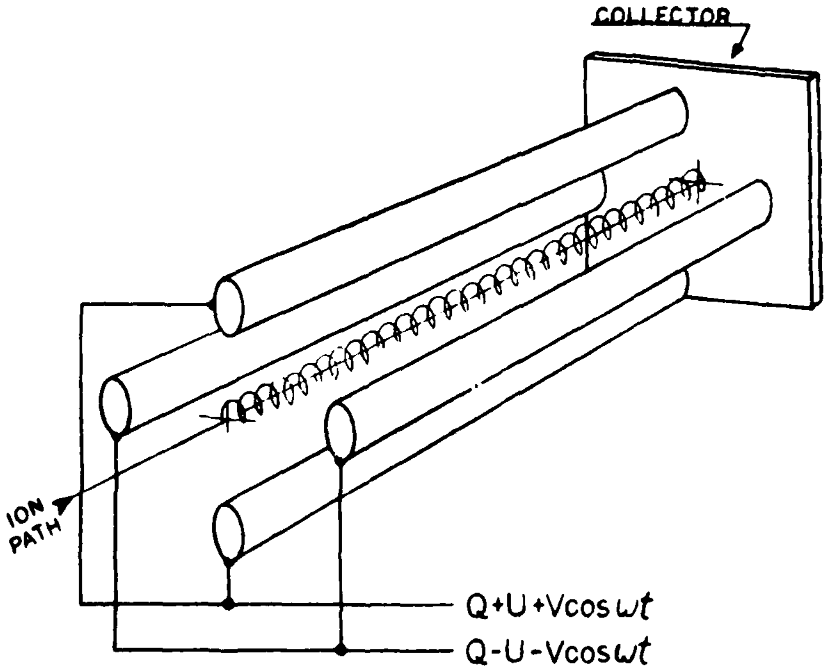

Figure 2. Quadrupole

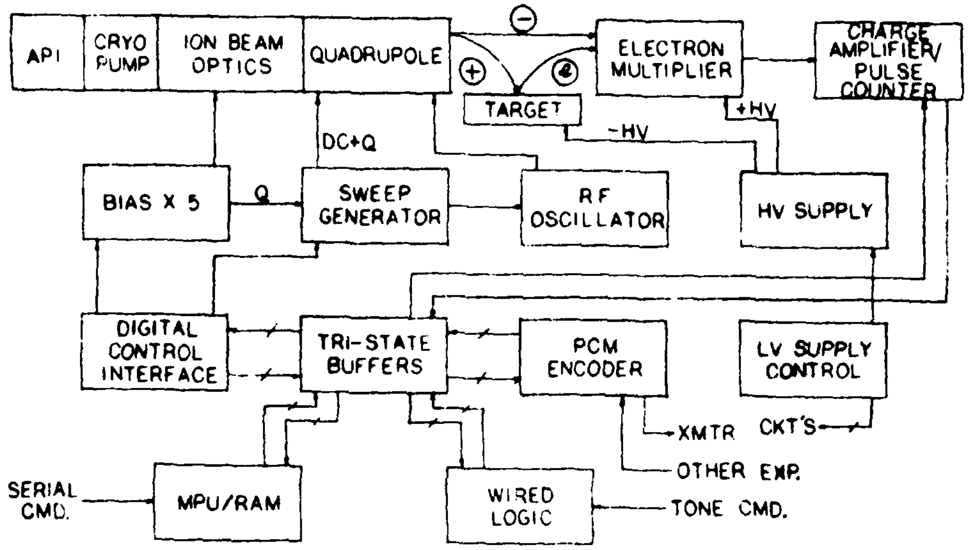

Figure 3. Ion Mass Spectrometer

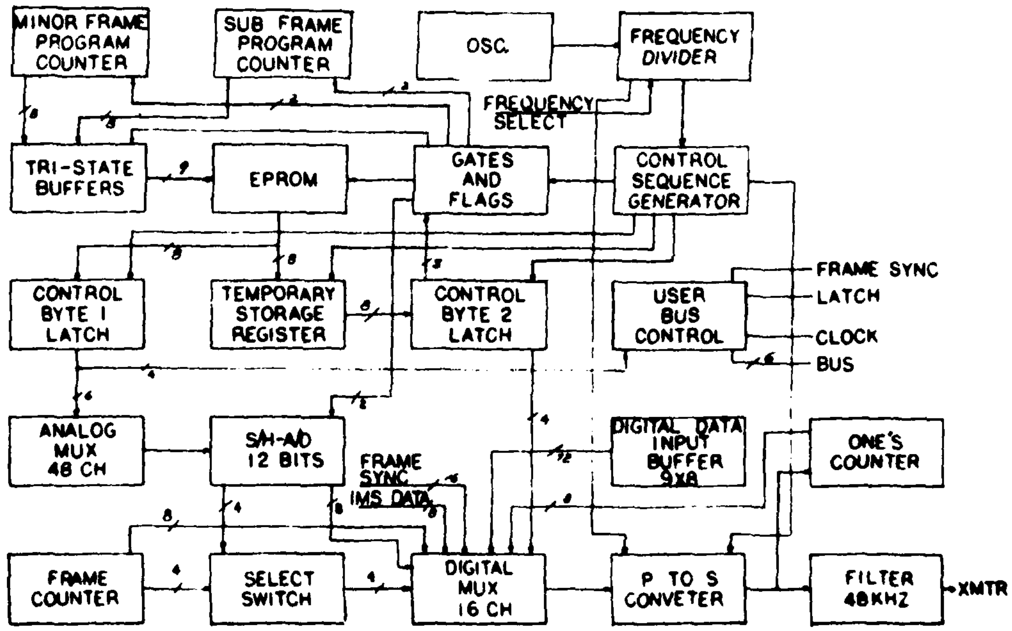

Figure 4. PCM Encoder